ACOUSTIC TRANSIENT SOURCE LOCALIZATION FROM AN AEROSTAT

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ABSTRACT

The Army Research Laboratory (ARL) has conducted experiments using acoustic sensor arrays suspended below tethered aerostats to detect and localize transient signals from mortars, artillery and small arms fire. The airborne acoustic sensor array calculates an azimuth and elevation to the originating transient, and immediately cues a collocated imager to capture the remaining activity at the site of the acoustic transient. This single array's vector solution defines a ground-intersect region or grid coordinate for threat reporting. Unattended ground sensor (UGS) systems can augment aerostat arrays by providing additional solution vectors from several ground-based acoustic arrays to perform a 3D triangulation on a source location. The aerostat array's advantage over ground systems is that it is not as affected by diffraction and reflection from man-made structures, trees, or terrain, and has direct line-of-sight to most events.

INTRODUCTION:

ARL has developed unattended ground sensor technology that gives the soldiers enhanced situational awareness, and persistent reconnaissance, surveillance, and target acquisition (RSTA). Discrete or arrays of sensors such as acoustic, seismic, magnetic, electrostatic, infrared tripwires, E/O images, can be processed to detect, classify, identify, and track targets of military significance. The Acoustic Signal Processing Branch of ARL has focused primarily on acoustic sensor arrays to detect and localize vehicles and transient events from mortars, rockets, and weapons firing. ARL has developed acoustic systems to support soldiers in the areas of mortar/rocket detection and sniper detection. These systems have either been used as UGS, or ground vehicle mounted. We realized that elevating the sensors onto an aerostat can improve localization and detection performance by removing some of the signal degradation caused by ground absorption, reflections and multipath from urban buildings, and terrain/vegetation interactions. Additionally, when attempting to fuse acoustic and imager data, the elevated array gives electro-optics direct line of sight to the targets of interest.

ARL conducted three major experiments using airborne acoustic sensor arrays to detect and localize tactically significant events on the ground: Aberdeen Proving Grounds (APG1), Yuma Proving Grounds (YPG2 and YPG3).

APG1: WIND NOISE AND ELEVATED SNR

The APG-1 experimental hardware, as shown in figure 1, was intended to characterize the wind noise environment and determine if there was a signal-to-noise (SNR) enhancement by elevating the traditional UGS to a height of 500 feet. This experiment **[1]** had data loggers to record 4-ch acoustics (mounted on 0.5-m tetrahedral), GPS, and roll/pitch/yawl of the payload. The balloon only had a 16-pound payload, and was very unstable in even low-moderate wind conditions.

Figure 1. First balloon used for signature collection and wind noise evaluation.

Post-processed results indicated that the aerostat array had a significant increase in SNR of ground vehicles over the UGS, as shown in figure 2. The spectrograms clearly show that the aerostat-collected SNR of vehicular targets has increase in amplitude. The harmonic features also present themselves earlier, and remain longer in time, which indicates an increased detection range.

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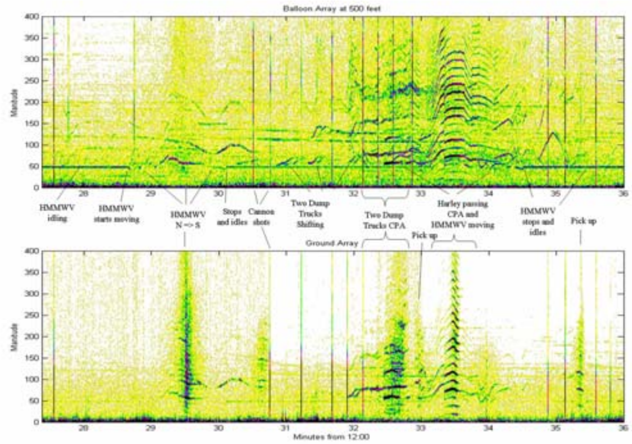

Figure 2. Spectrogram comparison of airborne (upper) vs ground sensor (lower) detection of ground vehicles.

Figure 3 shows the balloon/ground sensor comparison for transient signal amplitudes as the balloon is lowered from 500 feet to the ground. The received signal strength at the aerostat decreases with height, yet the ground sensor remains relatively constant throughout.

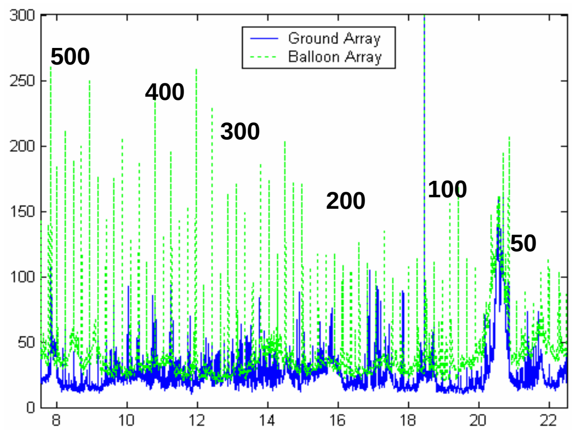

Figure 3. Transient amplitude variations due to altitude.

Although acoustic array data was collected on the balloon, no attempt was made to do transient localization with this data because of platform instabilities.

YPG2: IMPROVED PAYLOAD

A prototype aerostat-mounted acoustic array, shown in figure 4 was tested at YPG to altitudes as high as 2000-feet as part of Army collaborations and to support the NATO TG-53 signature collection exercise. Acoustic waveform data were collected simultaneously by aerostat and ground-based sensor arrays for comparing wind noise, turbulent/laminar flow effects on windscreens, signal to noise (SNR) related parameters, structure resonances, and atmospheric effects on propagation. The test consisted of the firing of mortars, artillery, and small arms at sites approximately 3, 7, and 9 kilometers from the aerostat array. The terrain was flat desert with sparse vegetation and three foot deep gullies. The raw acoustic data from the aerostat was processed with an algorithm that detected impulses and produced a bearing and elevation to the source. The aerostat's sampled GPS position and orientation were used to relate the acoustic bearing and elevation solution vector to ground truth data.

Figure 4. Two array systems for transient localization on 25' diameter balloon, relative position of array hanging from balloon.

YPG2: NOISE COMPARISON BETWEEN AIRBORNE/GROUND SENSORS

Figure 5 shows the effects of wind on the ambient noise floor of the UGS and airborne systems. Under low wind conditions, as seen in the upper trace of figure 5, shows that with the exception of a couple structural and tether resonances, the noise floors are comparable. This implies that the detection algorithm would not need to be modified and sensitivity of the airborne sensor would be comparable to the UGS. The lower trace in figure 5 shows that under higher wind conditions, the airborne sensor shows an elevated broadband noise. Some of this noise is believed to be due to platform instabilities and mechanical vibrations of the array arms. Care was taken to eliminate these in YPG3. The higher noise floor implies that there needs to be a larger signal present for the current detection algorithm to discern a transient over the elevated ambient noise floor. This does not necessarily imply that detection range has decreased, since the path losses of transients reaching the array may be less and therefore still arrive with sufficient signal strength.

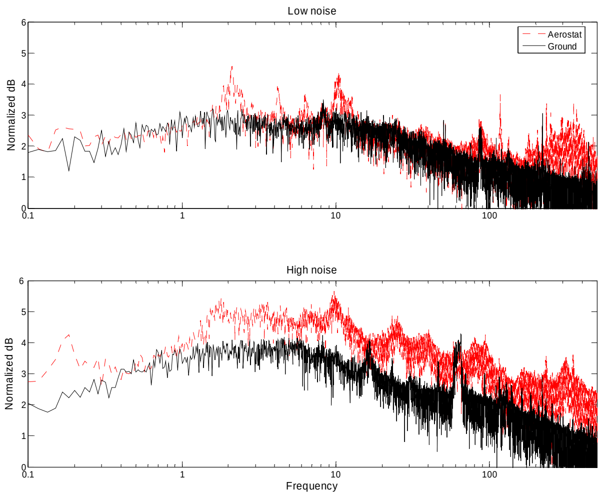

Figure 5. FFTs of low and high noise data from aerostat and ground systems.

An aerostat in a more laminar flow regime has a less turbulent noise field than a ground sensor in the turbulent boundary layer resulting from terrain/vegetation interactions. This can be an advantage for the aerostat in reducing wind noise effects if the sensor platform and structure resonances seen in figure 5 can be removed.

MET EFFECTS & MODELING

Experimental results showed that meteorological (MET) conditions helped or hindered the detection of acoustic events. Figure 6 shows some of the environmental effects that contribute to sound propagation. Diffraction over/around buildings or hills, multipath, temperature gradients, wind speed, and direction all play a major role in the path and signal characteristics.

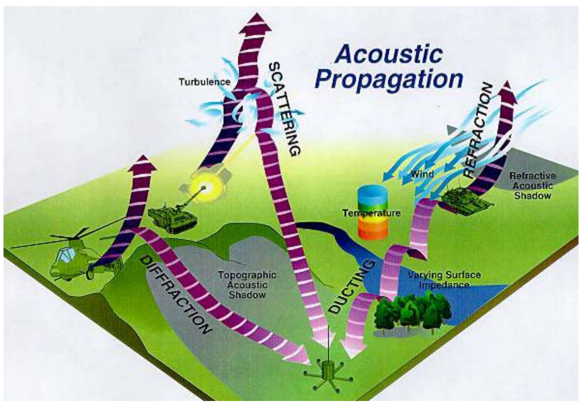

Figure 6. MET & terrain conditions affecting sound propagation.

Using acoustic and propagation models from the Acoustic Battlefield Decision Aid (ABFA) tool, we can predict the acoustic detection performances at different elevations and on the ground under a variety of atmospheric conditions **[2]**. Fig. 7 shows the predicted detection ranges for a 100 Hz signal at different altitudes from ABFA for a specific time of day at a specific location, e.g., 8 am on 24 June 2004 at Spesutie Island, APG. Actual MET data were used as input into ABFA to generate these results. In this example, where we have upward diffraction due to the temperatures being cooler at higher altitudes, we can definitely observe an increase in detection ranges at elevated heights. Specifically, the detection range is approximately four times at 80 m elevation and approximately 5 times at 320 m, respectively, compared to the detection range at 0.1 m above the ground.

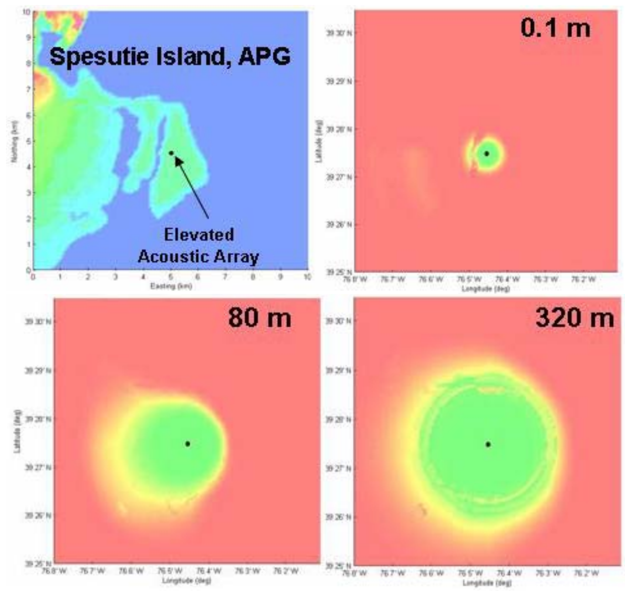

Figure 7. Results from ABFA: Elevation map and detection probabilities for a wheeled vehicle at various sensor altitudes.

Figures 8 and 9 show that MET variations can actually reverse the measured amplitude ratios between ground and airborne sensors. The two different MET conditions represented in figure 9 correspond to the two amplitude comparisons in figure 8. The upper plot in figure 8 shows waveforms for a 120mm mortar on Tuesday (the "solid line" MET profile in figure 9). This sound speed profile decreases with height, which refracts the acoustic wave upwards to create an increased amplitude and higher frequency content for the aerostat. The lower plot in figure 8 shows waveforms for a 120mm mortar at over twice the range on Thursday (the "dashed line" MET profile in figure 9). This sound speed profile increases and decreases with height, which refracts the acoustic wave downwards first, then upwards, and finally downwards resulting in two sound ducts. This complicated sound duct environment caused the aerostat signal to be attenuated; especially in the higher frequencies. Meanwhile the propagating acoustic wave refracted toward the ground, resulting in the increased ground sensor amplitude and high frequency content.

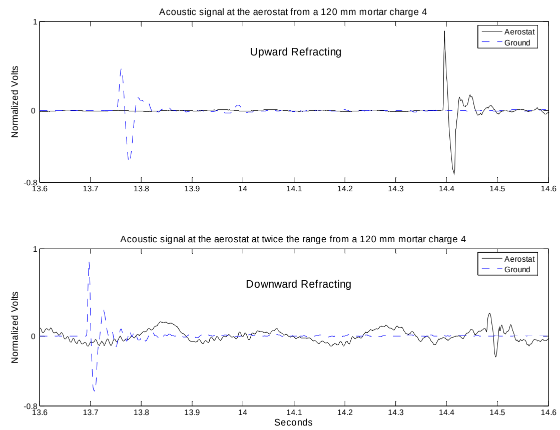

Figure 8. MET effects on signal amplitude.

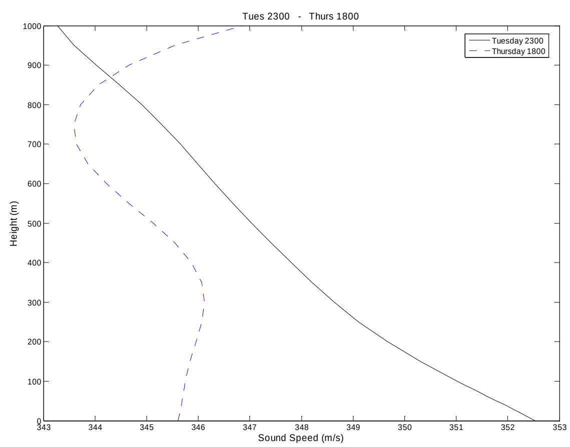

Figure 9. Sound speed profile for the data in figure 8.

The signal amplitude measured on the ground at twice the range is comparable to the signal levels measured at the aerostat for similar source. The detection sensitivity on an elevated or ground array is shown to be affected by the refraction of the propagating acoustic wave upward or downward, depending on the MET conditions between the source and array. This refraction also changes the measured direction-of-arrival of the acoustic wave front, which also affects the solution accuracy.

The acoustic signal is commonly refracted upward during the day because of higher surface temperatures and continues refracting upward until the nocturnal temperature inversion occurs. This enhances the elevated platform detection sensitivity during that time for all source bearings. Upper level wind shear can produce sound ducts and refraction that are either favorable or unfavorable to elevated detection, depending on the wind directions and the source bearing. Weather stations at both the aerostat and on the ground may provide enough information to adaptively reduce MET-induced errors. Conditions effecting detection and localization can be modeled using the Acoustic Battle Field Aid (ABFA) program.

YPG2: DETECTION & LOCALIZATION RESULTS

Figure 10 shows the aerostat detection and solution bearing accuracies for tactically significant events measured above the Yuma desert in YPG-2. The initial testing of the aerostat array had very good detection probabilities and solution bearings were usually within ten degrees, which is accurate enough to cue an imager to the acoustic event and have the source be within the camera's field of view. Image processing techniques with fusion algorithms can enhance localization within the camera's field-of-view.

This YPG2 experiment provided a wealth of diverse signature data with complete ground-truth. These data will be used to improve ARL's detection, localization, classification, and wind-reduction algorithms. This aerostat system flew for the first time during this test, and the results are very good considering the difficulties of motion artifacts and positional variations due to MET and platform mounting.

YPG-2 Observations: Applied to YPG-3

Aerostat and ground arrays have been compared with good results; however aerostat improvements can reduce noise and improve algorithm accuracy. MET conditions affect sensitivity and accuracy of both ground and air systems. The accuracy effects can be compensated for using local MET information. Upward refraction that is commonly seen during the day will improve the elevated array sensitivity. Area wind conditions add directional and layered effects to the sound speed profile which complicate the prediction of the elevated or ground system sensitivity.

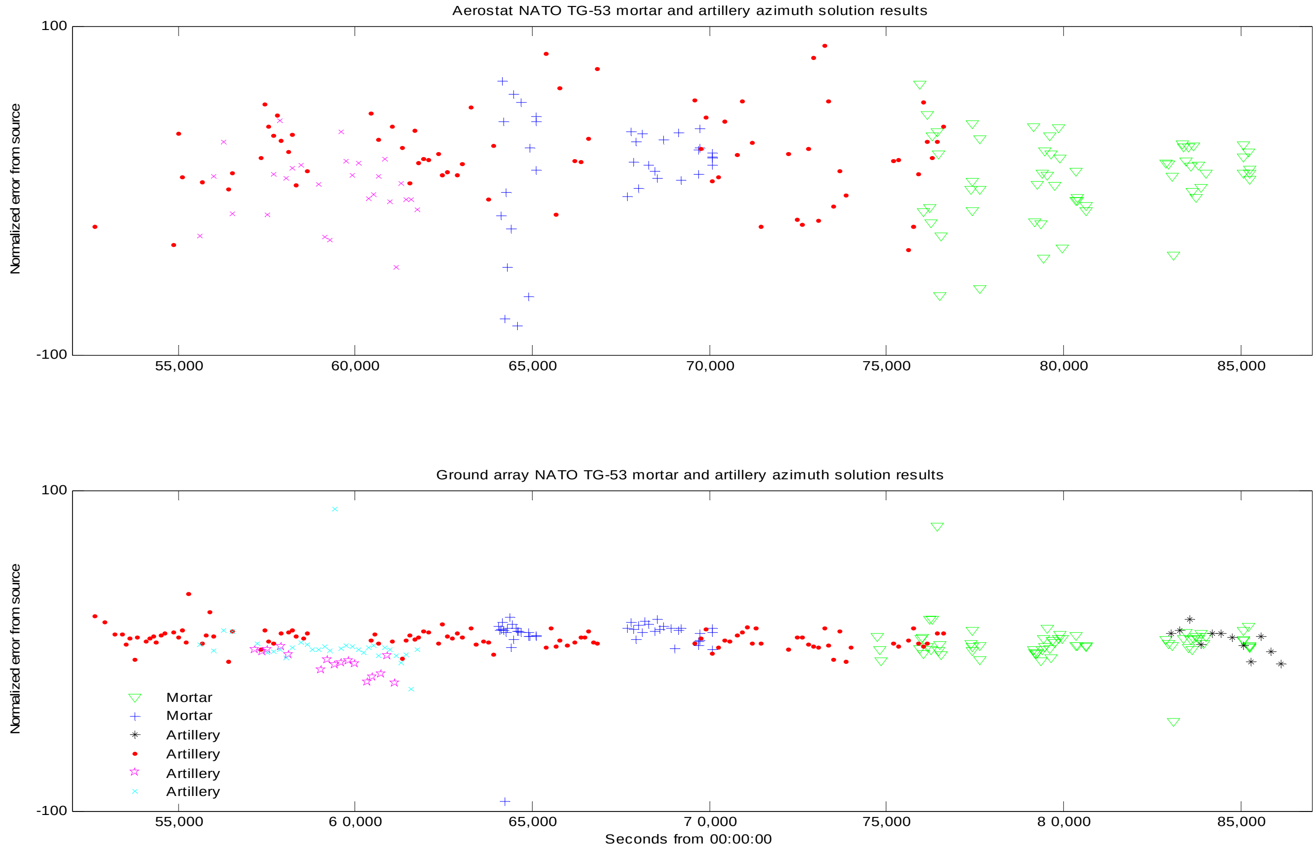

Figure 10. Aerostat and ground bearing accuracy for YPG-2.

The array shape was not a pure tetrahedral, and therefore will not provide complete omnidirectional beam-response. For YPG2, each of the four arms was one meter in length, and therefore the acoustic center for the four mics does not coincide with the center of the geometric sphere that intersects all four mics. For YPG3 we extended the vertical microphone support to a length of 1.414m to create an acoustic centered tetrahedral and provide a more uniform directivity response. More microphones on the sphere would improve SNR and localization, but will not be implemented in the near future.

Frame motion from wind-induced oscillations will be reduced by adding an additional stabilization line from the cantilevered end of the payload to a point on the "sail" strength line, which will limit the amount of motion allowed. Wind noise from array arm vibration will be mitigated by adding three stiffening shafts that connect the approximate midpoint of each arm to the midpoint of the vertical arm. This added considerable rigidity to the microphone arms, and reduced most wind-induced motion. Wind noise from turbulence at the mics was not improved from the previous tests, since the same 6-inch diameter spherical open cell foam windscreens were used, but the turbulence of the wind near the array was measured with a 3-D anemometer.

YPG-3 Description:

Sources used for the YPG-3 test were 150mm and 81mm mortars launches and detonations, a propane cannon firing every 16 seconds for periods of time, a helicopter, electric and gas powered UAV, and an SUV. The YPG-3 payload in figure 11 show the improvements applied from the YPG-2 test with the addition of a ballcam imager and a 3-D anemometer. The payload was suspended from the aerostat as before with the addition of the stabilization line to limit swinging. The system software had improved sample rates to improve orientation and GPS compensation.

YPG-3 Observations:

There is an obvious reduction in noise contributed from array arm vibration and the limited motion of the payload as seen by comparing the YPG-2 noise in figure 5 and the YPG-3 noise in figure 12. The resonance peaks from 2 to 10 Hz caused by the frame/arm vibration on the YPG-2 payload have

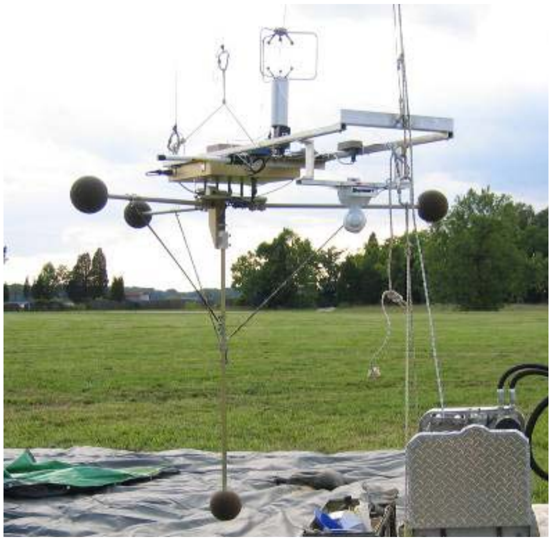

Figure 11. Complete payload.

decreased in amplitude and shifted to a higher frequency of around 20 Hz. The main contribution to the noise for the YPG-3 array is the longer vertical mic arm as seen by the larger resonant signal in the acoustic data. Given the conditions are not the same for a comparison, the increase in broad band array noise for the aerostat array relative to the ground array is similar for both YPG-2 and YPG-3 measurements. This increase in broad band noise for elevated arrays would have to be treated with improved wind screens to reduce the effect on detection sensitivity.

A comparison of the wind speed data from the 3-D anemometer on the payload with a ground MET station 10 km to the east shows similar amplitudes for most of the test. A 3-D anemometer on the ground below the aerostat failed to work so a direct comparison to the ground environment is not possible. The aerostat MET data was sampled at 10 kHz which allowed any turbulent change in wind speed and direction to be seen. A preliminary look at the data shows more turbulence near the aerostat array than expected. The foam wind screens being used now are good in a turbulent environment. **[3]** An investigation of the benefits of using the aerostat MET data and ground MET to correct the solution vector for local MET conditions is also being performed. The aerostat array consistently had a much higher acoustic signal levels than the ground array for the same source. This indicates the higher temperature near the ground resulted in upward refraction of the acoustic signal as expected during the day.

The acoustic signals from the four mics are used by the detection and localization algorithm to provide solution bearings and elevations that describe vectors toward the source of the acoustic signal. These solution vectors were corrected for the orientation and location of the acoustic array at the time of the signal incidence. The difference between the bearing solutions and the actual bearings determined from ground truth are shown in figure 13. The differences between the aerostat and ground plots are very similar until the higher wind conditions later in the day caused the increase in frame motion as measured by the orientation sensor and the increase in broad band noise seen in Figure 12. The difference between the YPG-2 aerostat solutions in figure 10 and the YPG-3 aerostat solutions in figure 13 dramatically show the bearing accuracy improvement between the two tests. The bearing accuracy for the ground systems in both tests is similar as would be expected for the same system. The less accurate aerostat solutions for the propane cannon later in the day are a product of the lack of low frequency content in the signal and the hardware and algorithm specifications targeting lower frequency impulse sources as well as the increased wind speed.

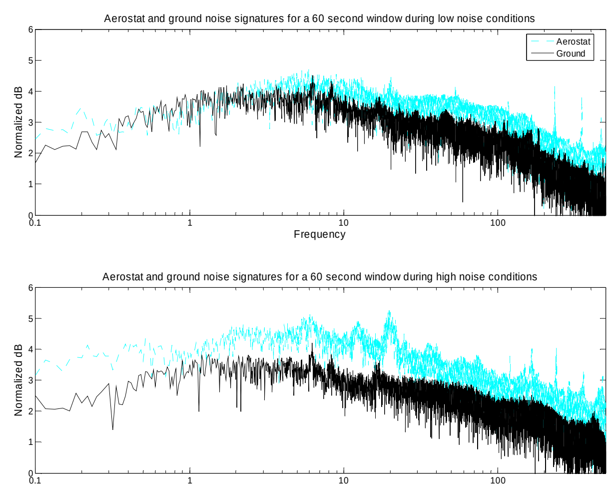

Figure 12. FFTs of low and high noise data from aerostat and ground systems.

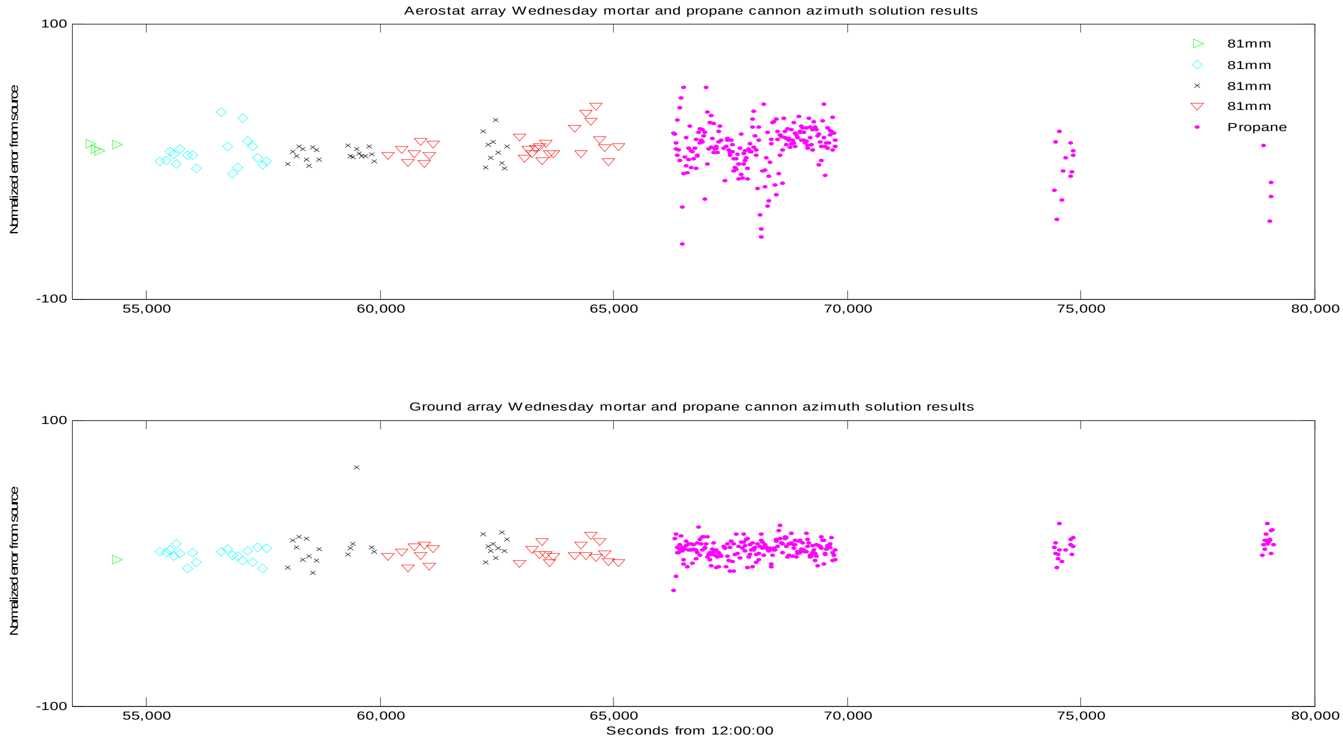

Figure 13. Aerostat and ground bearing accuracy for YPG-3.

The corrected solution for both the bearing and elevation to the target was used to determine an intersection point with the ground (assuming a plane) and the results are shown in figure 14. The plot shows the significance of the elevation accuracy on the localization solution by the radial scattering of solutions.

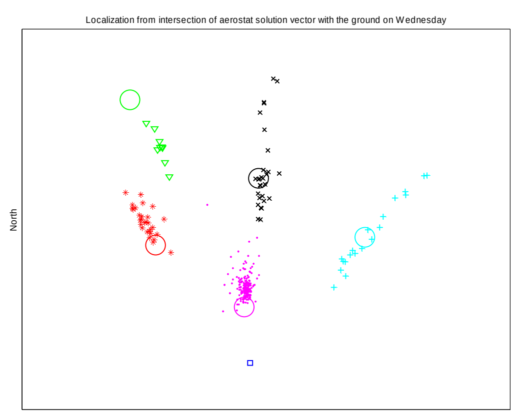

Figure 14. Localization from aerostat.

The uncorrected solution vector was used to cue the ball cam to take pictures of the source. The camera panned to the vector and took a 3/4 zoom and a full zoom picture. Most of the images above 1/2 zoom were blurred by motion. Figure 15 shows images taken when the camera was cued to mortar shell detonation and the dust cloud allows the recognition of the event. The time involved autonomously in panning to the solution vector allowed the payload motion to create an offset to the source that can be corrected. More expensive camera systems that interface with INS will track the localization coordinates on the ground to provide a stabilized continuous image of the source.

Figure 15. Explosion dust-clouds captured after aerostat's imager was acoustically cued by the airborne array to the transient event's AZ/EL.

DISCUSSION AND FUTURE WORK:

Warning aircraft from flight paths that would approach the aerostat safety zone is an issue to be investigated. Tether avoidance data was collected with both airborne and ground based sensor arrays for a helicopter during the test. The aerostat acoustic array solution vectors found using a 3-D vehicle tracking algorithm, with either passive range approximation or UGS collaboration, will define 3D trajectory of approaching aircraft and alert the aircraft when encroaching the aerostat safety zone.

MET conditions can have a profound effect on the sensitivity of the system and accuracy of the vector solutions. An investigation into the benefits of incorporating local MET information to improve solution accuracy will be done. A night test would provide a data set to determine the effect of night time MET conditions on event detection and accuracy.

The reduction of the wind noise in the aerostat acoustic array data will continue to be studied. Measuring the MET conditions at the aerostat array has provided information that will be used to improve the wind screens, decrease package turbulence, or change the position or shape of the array.

Sufficient data has been collected during the YPG-2 and YPG-3 tests to allow continued work on the improvement of the detection and localization algorithms and possible work on a classifier algorithm.

CONCLUSIONS:

A more stable aerostat platform with a more precise inertial navigation system will enable airborne acoustic localization accuracies to approach current ground sensor bearing accuracies. Experimental collaborations are also beginning for integrating acoustic sensors onto much larger aerostats. YPG-3 showed that we successfully acoustically cue an airborne camera to the transients and that we are capable of calculating the ground coordinate of the transient based on aerostat’s instantaneous position and attitude.

The aerostat has the same or slightly better accuracy capability as the ground sensor array because both arrays use the same localization algorithm, hardware, and similar array configuration. The longer center mic arm will increase the elevation accuracy which isn't as important to ground system operation. The array stability is the main contributor to the solution error. The increase in noise from wind affects the sensitivity more than the accuracy, it is often more than offset by the increase in sensitivity for typical conditions.

An airborne array can be multi-functional. In addition to the large caliber weapon and explosion detection and localization, the airborne array can provide helicopter and other aircraft tether avoidance and tracking, small arms firing detection, vehicle tracking, etc. Integration of local MET sensor and terrain information with the use modeling algorithm such as ABFA or a sound speed profile calculator can improve localization accuracy as well provide indication of the detection range and accuracy for the present conditions.

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